Why NOνA

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1 Reactor

At the end of 2008, the Double Chooz reactor neutrino ($\bar{\nu}_e$) disappearance experiment will start taking data with the far detector only. The near detector is scheduled to be operational approximately one year later. Thus, the first results will most likely be available mid-2010 with a maximum sensitivity to $\sin^2 2\theta_{13} \sim 0.06$ (90% CL). The Daya Bay reactor neutrino disappearance experiment is expected to have operational detectors in one of the near halls by end of 2009 and operational detectors in the other near hall and the far hall within about one year. The expectation is that by mid-2012 both Double Chooz and Daya Bay will either have tantalizing evidence for none zero $\sin^2 2\theta_{13}$ or will be able to set a limit on $\sin^2 2\theta_{13}$ at the 0.03 to 0.04 level (90% CL). The ultimate sensitivity of the Double Chooz experiment in $\sin^2 2\theta_{13}$ is 0.03 at 90% CL but will probably take a number of years to reach. Whereas, the ultimate sensitivity of the Daya Bay experiment in $\sin^2 2\theta_{13}$ is just below 0.01 at 90% CL but this will probably take many years to reach due to the fact it requires a very detailed understanding of the systematic errors as the $\bar{\nu}_e$ survival probably at the far detector is within 1% of unity.

2 T2K

Meanwhile, the T2K ν_μ to ν_e appearance experiment operating near the first oscillation maximum will start taking data, mid 2009, in the SuperKamiokande water Cerenkov detector using a new off axis neutrino beam from the JPARC accelerator complex. The baseline is 295 km, the mean neutrino energy is 0.65 GeV and the spread about 20%. The SuperK detector (as well as the NOvA detector) is situated off the beam axis so as to reduce the ν_e fake rate due to π^0s produced in higher energy NC interactions. The beam power for this experiment is expected to slowly ramp to 700 kW after a number(???) of years of operation. With six years of neutrino only data taking the $\sin^2 2\theta_{13}$ sensitivity curve[1] for T2K ranges from 0.02 to 0.004 at the 90% CL. This sensitivity curve corresponds to a value of P($\nu_\mu \to \nu_e$) $\sim$0.5% whereas the ν_e beam contamination is approximately 1%. The factor of five range in the $\sin^2 2\theta_{13}$ sensitivity is caused by our complete ignorance of the value of the CP violating phase in the MNS mixing matrix. See Figure 1. Due to the small matter effect for this experiment the sensitivity curves are approximately independent of the neutrino mass hierarchy. No anti-neutrino running is expect in the initial run of T2K due to the reduction in the flux and the cross section when switching to anti-neutrinos at the beam energy of this experiment.

[1] Assuming $\sin^2 \theta_{23} = 1/2$.

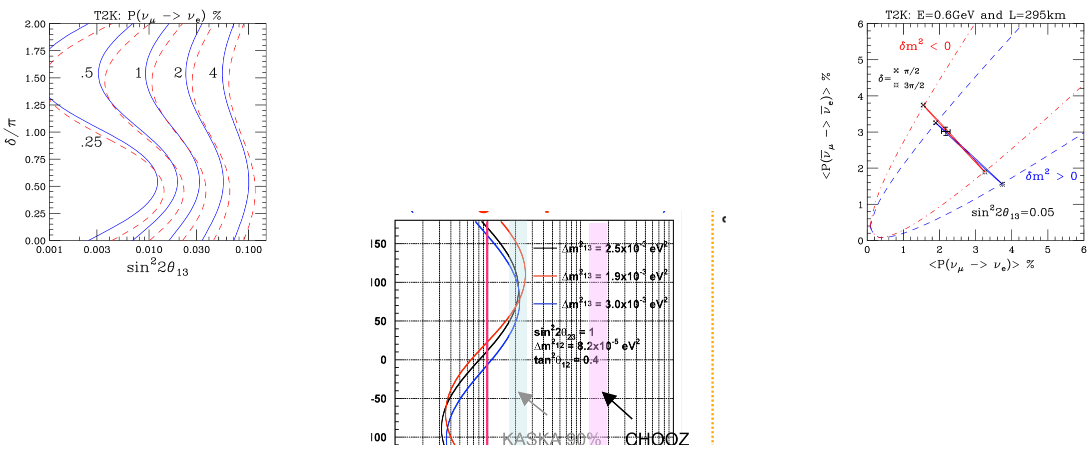

Figure 1: The left panel is the iso-probability contours for T2K as a % for the neutrino channel. The solid (blue) line is for the normal hierarchy whereas the dashed (red) line is for the inverted hierarchy. The matter effect is small for T2K. The middle panel is the sensitivity claimed by the T2K experiment at the 90% C.L. which corresponds to approximately the 0.5% iso-probability contour of the left panel. The right panel shows the correlation between neutrino and anti-neutrino oscillation probabilities in T2K. The separation between the normal hierarchy (between the blue dashes) and the inverted hierarchy (between the red dotdashes) is small because of the small matter effect.

3 NOvA

The NOvA experiment is also a ν_μ to ν_e appearance experiment, near the first oscillation maximum, consisting of 15 ktons of active liquid scintillator positioned 810 km from Fermilab. The detector will be placed 12 km off axis from the NuMI beam such that the mean neutrino energy will be 2.0 GeV with a spread of about 15%. For the NOvA experiment, due to its much higher energy, matter effects are a factor of three larger than for T2K. Also, due to the higher energy, NOvA can also run with anti-neutrinos and obtain a reasonable flux times cross section in the far detector. The matter effect enhances (suppresses) $\nu_\mu \to \nu_e$ for the normal (inverted) hierarchy and vice versa for the corresponding anti-neutrino oscillation. The combination of large matter effects and being able to run with anti-neutrinos is unique to NOvA and allows NOvA to determine the neutrino mass hierarchy over a sizeable range of the CP violating parameter, δ. Figure 2 shows the oscillation probabilities for the neutrino and anti-neutrino channels together with the correlation between these probabilities.

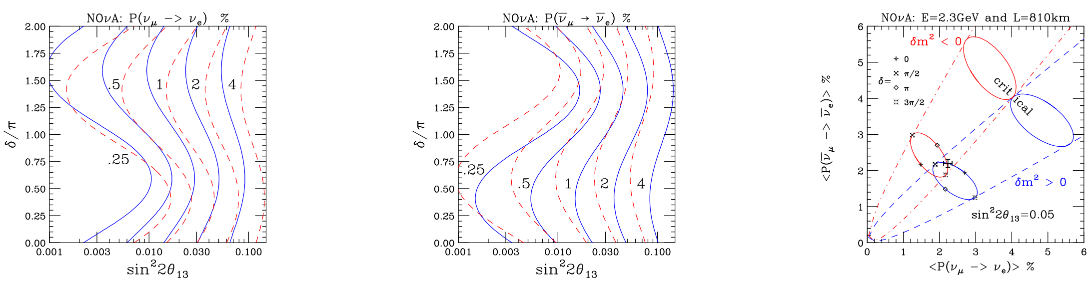

Figure 2: The left and middle panels are the iso-probability contours for NOνA as a % for the neutrino (left) and anti-neutrino (middle) channels. The solid (blue) line is for the normal hierarchy whereas the dashed (red) line is for the inverted hierarchy. The right panel is the bi-probability plot showing the correlation between the two probabilities. The matter effects and hence the separation between the hierarchies is 3 times larger for NOνA than T2K due to the fact NOνA has three times the baseline.

From the right hand panel of this figure it is clear that when the allowed regions for the normal and inverted hierarchy are well separated then NOvA has can determine the neutrino mass hierarchy with sufficiently precise measurements of the oscillation probabilities. Whereas, when the allowed regions for the two hierarchies overlap then NOvA alone cannot determine the hierarchy. However, when the NOvA measurements are combined with measurements from T2K and/or Daya Bay, which are inherently insensitive to the hierarchy, the hierarchy can be determined for an additional range of parameters.

The measurement of the oscillation probability is determined from the number of signal events in the far detector which depends on many beam and detector parameters: number of protons on target, detector fiducial mass, detector efficiency, beam contamination, fake rates etc. Also, the uncertainty on the measurement of the oscillation probability in these experiments is dominated by signal event statistics. All of these issues have been included in the Monte Carlo that has been used to determine the sensitivity curve for the NOvA experiment. Figure 3 is the sensitivity curve for both hierarchies to non-zero $\sin^2 2\theta_{13}$ at the 90% C.L. assuming equal running of neutrinos and anti-neutrinos.

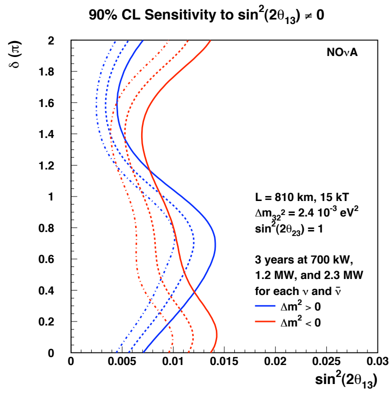

Figure 3: The sensitivity curves for the NOvA experiment assuming 3 years of running for neutrino and anti-neutrino at the 90% CL for three different assumption about beam power 0.70, 1.2 and 2.3 MW. The blue lines are for the normal hierarchy whereas the red lines are for the inverted hierarchy.

Comparing fig. 3 to the iso-probability figures one sees that the NOvA experiment is also sensitive to oscillation probabilities down to approximately 0.5% and that the sensitivity curve depends in detail on which hierarchy nature has chosen. The ultimate sensitivity for NOvA is similar to that of T2K. However, at these small values of oscillation probability, when there is limit evidence of non-zero $\sin^2 2\theta_{13}$ it will be important to have addition information using different detector technology with different systematic errors.

At values of $\sin^2 2\theta_{13} > 0.05$, NOvA alone can determine the mass hierarchy at the 95% CL center around $\delta = 3\pi/2$ for normal hierarchy and $\delta = \pi/2$ for the inverted hierarchy, see Fig. 4. When combined with T2K the range in δ is extended and with increase beam power for NOvA covers the full 360 degrees for $\sin^2 2\theta_{13} > 0.06$.

At intermediate values of $\sin^2 2\theta_{13}$, say between 0.02 and 0.05, NOvA in combination with T2K and Daya Bay can provide constraints on the allowed region for the CP violating phase as well as hints on the mass hierarchy. See an example in Fig. 5. Information from all three experiments is very important to provide information for future running and experiments. If $\sin^2 2\theta_{23}$ is not identically one, then having information from all three experiments, Daya Bay, T2K and NOvA, is even more critical, since there is an extra degeneracy to resolve.

In summary, NOvA's beam energy and baseline allows for both anti-neutrino and neutrino running with significant matter effects and this combination provides unique and powerful information for determining the neutrino mass hierarchy and constraining the size of CP violating in the neutrino sector.

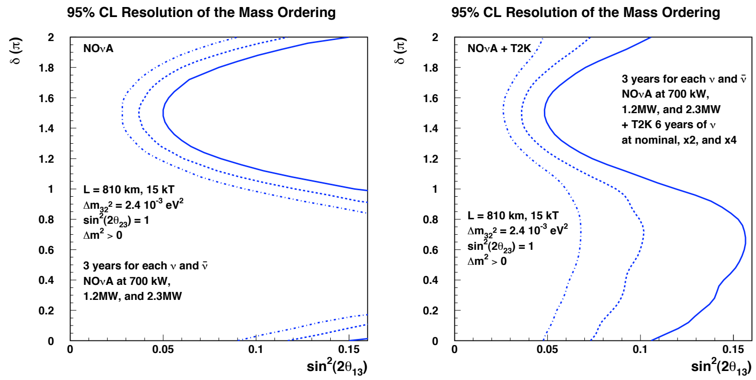

Figure 4: The NOνA 95% CL resolution limits for determining the neutrino mass hierarchy assuming it is normal using 3 years of running for both neutrinos and anti-neutrino with three different assumption about beam power 0.70, 1.2 and 2.3 MW. Left panel NOvA alone. Right panel NOvA plus T2K neutrino running. The inverted hierarchy limits are very similar to these but flipped about $\delta = \pi$.

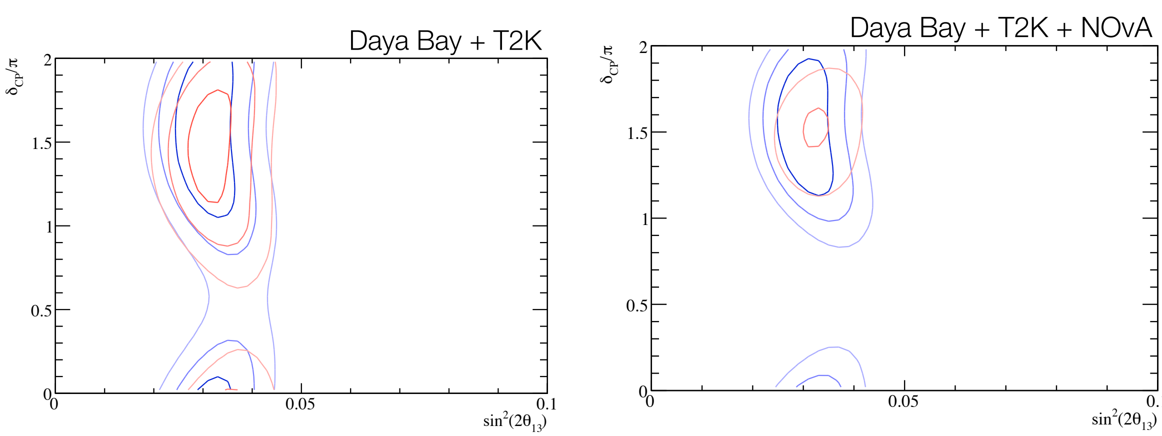

Figure 5: Allowed regions for Daya Bay plus T2K (left panel) and Daya Bay plus T2K Plus NOvA (right panel) assuming the normal hierarchy with $\sin^2 2\theta_{13} = 0.03$ and $\delta = 3\pi/2$. Even at this value of $\sin^2 2\theta_{13}$, the addition of NOvA reduces the allowed values of δ considerable at all CLs and also provides some hint (better than 1 but less than 2σ) of which of the two hierarchies is preferred. This example assumes nature has chosen $\theta_{23} = \pi/4$.